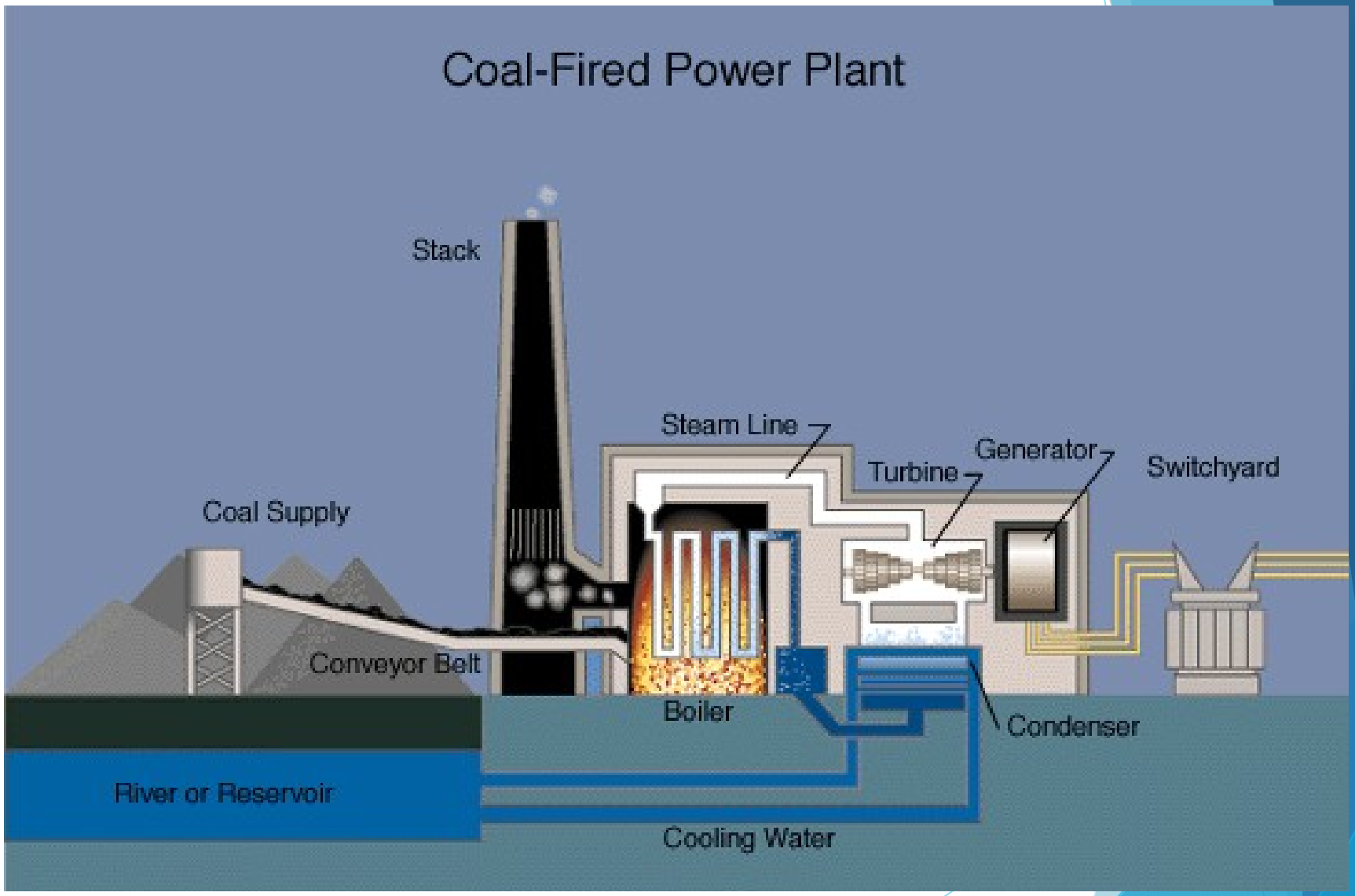
Nuclear Energy Basics

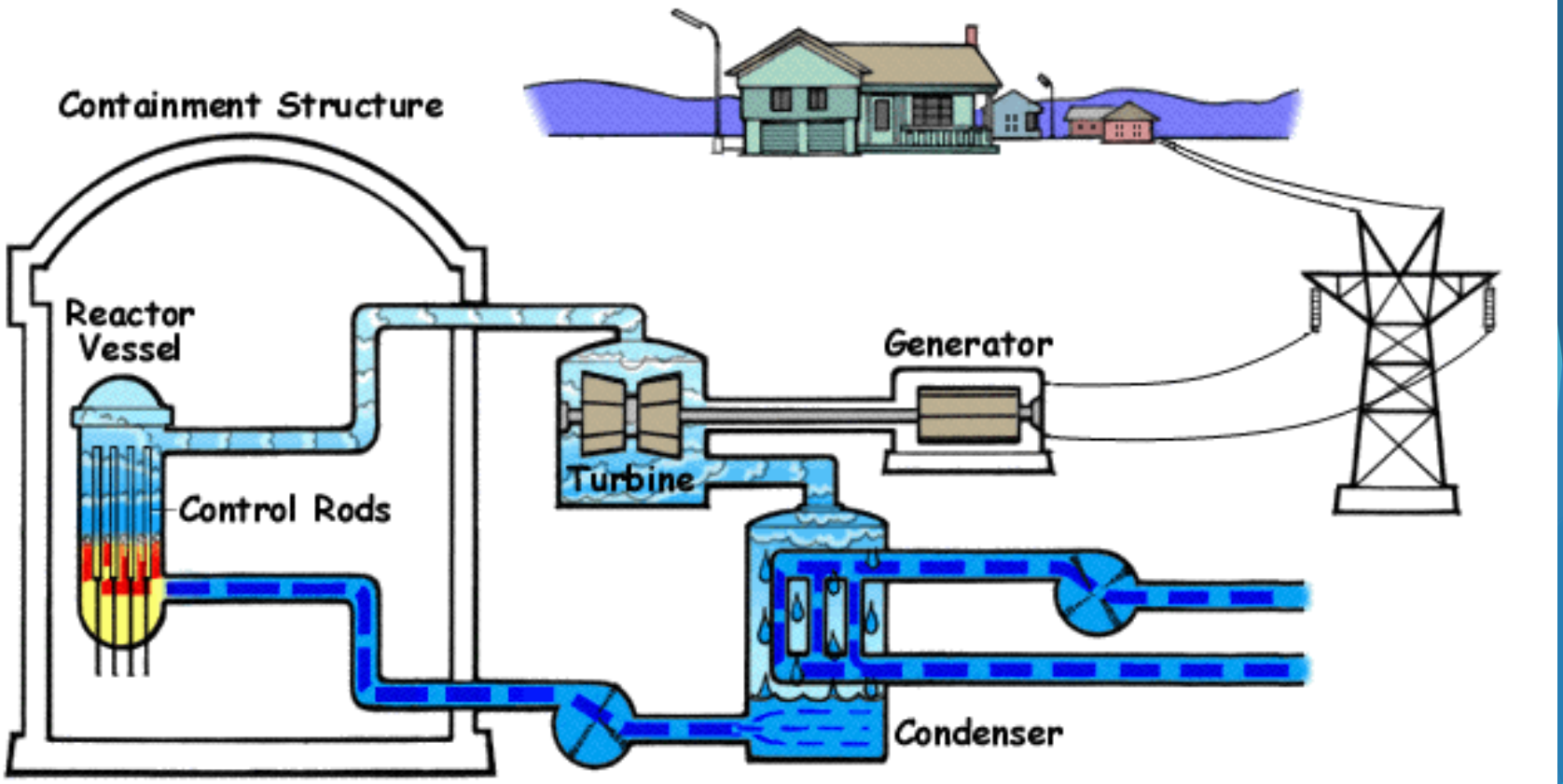
The Science and Facts of Nuclear Power

Jeffrey A. Mahn
Nuclear Engineer (Retired)
Albuquerque, NM USA
jamahn47@gmail.com

Nuclear Fuel Serves as a Heat Source in a Conventional Steam Cycle Power Plant to Generate Electricity


Coal-Fired Power Plant
Stack
Steam Line
Generator
Turbine
Switchyard
Coal Supply
Conveyor Belt
Boiler
Condenser
River or Reservoir
Cooling Water

Boiling Water Reactor Plant



Why Nuclear Power?

(Because $E = mc^2$)

Hydrocarbon vs. Nuclear Energy Production Comparison

Heat of Combustion for Methane

$CH_4 + 2\ O_2 \rightarrow CO_2 + 2\ H_2O$

Heat of combustion = $\Delta H_f\ CO_2 + 2\ \Delta H_f\ H_2O - \Delta H_f\ CH_4 - 2\ \Delta H_f\ O_2$

$= -890$ kJ/mol

(890 kJ/mol)/(16.0 g/mol) = 55.6 kJ per gram of CH_4

Fission Energy for U-235

$(200\ \text{MeV})(1.602\text{x}10^{-13}\ \text{J/MeV})(6.02\text{x}10^{23}\ \text{atoms/mol})$

$= 1.93\text{x}10^{10}$ kJ/mol

$(1.93\text{x}10^{10}\ \text{kJ/mol})/(235\ \text{g/mol}) = 8.21\text{x}10^{7}$ kJ per gram of U-235

Per gram of fuel, uranium fission produces about 1.5 million
times more energy than combustion of methane.

Energy Content of Fuels

One standard cubic foot (SCF) of natural gas	~1 x 10^6 Joules[a] (~2.4 x 10^7 J/lb)
One barrel of crude oil (42 gallons)	~6 x 10^9 Joules[b] (~2 x 10^7 J/lb)
One pound of coal	~1 x 10^7 Joules[c]
One pound of Uranium-235	~4 x 10^{13} Joules[d]

Refs: a Envestra Ltd., b IOR Energy, c The Physics Factbook, d Previous slide

Equivalent Fuel Requirements

Fuel Requirements for a 1000 MWe (3000 MWt) Power Plant

= 3×10^9 watts (thermal)

= 2.59×10^{14} Joules/day

Coal: ~13,000 tons/day (130 100-ton rail cars per day)

Oil: ~43,200 barrels/day (one oil supertanker every 1.5 months)

Natural gas: 259 million SCF/day (equivalent to ~44,800 barrels of oil per day or one oil supertanker every 1.5 months)

Uranium (as U-235): 8.3 lb/day

A 1000 MWe power plant will provide the electricity needs for ≈760,000 homes (Ref. U.S. Energy Information Administration, Dec. 6, 2011)

Coal: ~13,000 tons/day (130 100-ton rail cars per day)

Typical coal train of 100-120 cars is a mile long

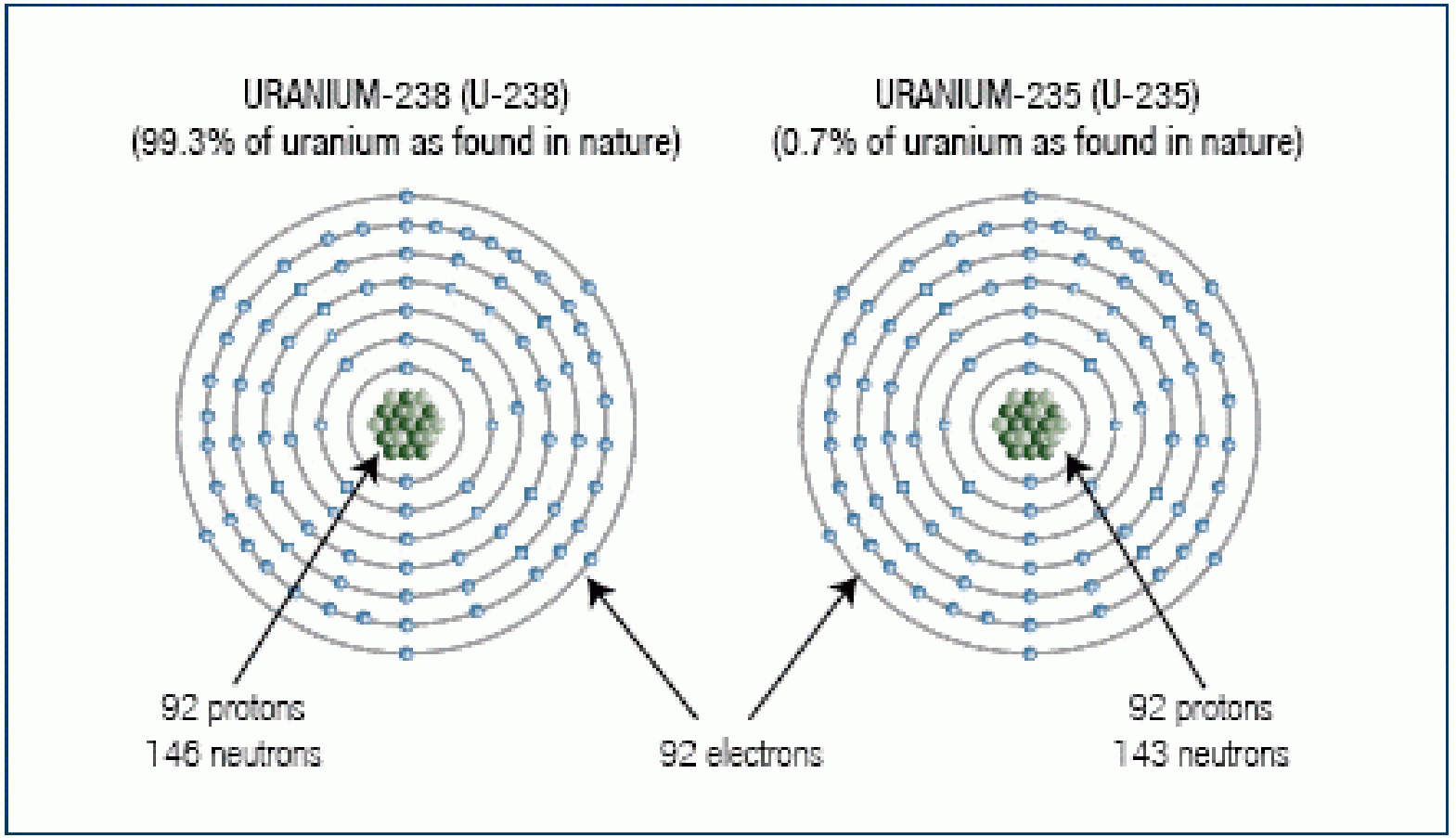
Oil: ~43,200 barrels/day (one oil supertanker every 1.5 months)

Oil supertanker capacity is 1.5 to 2 million barrels of oil

The Fission Process

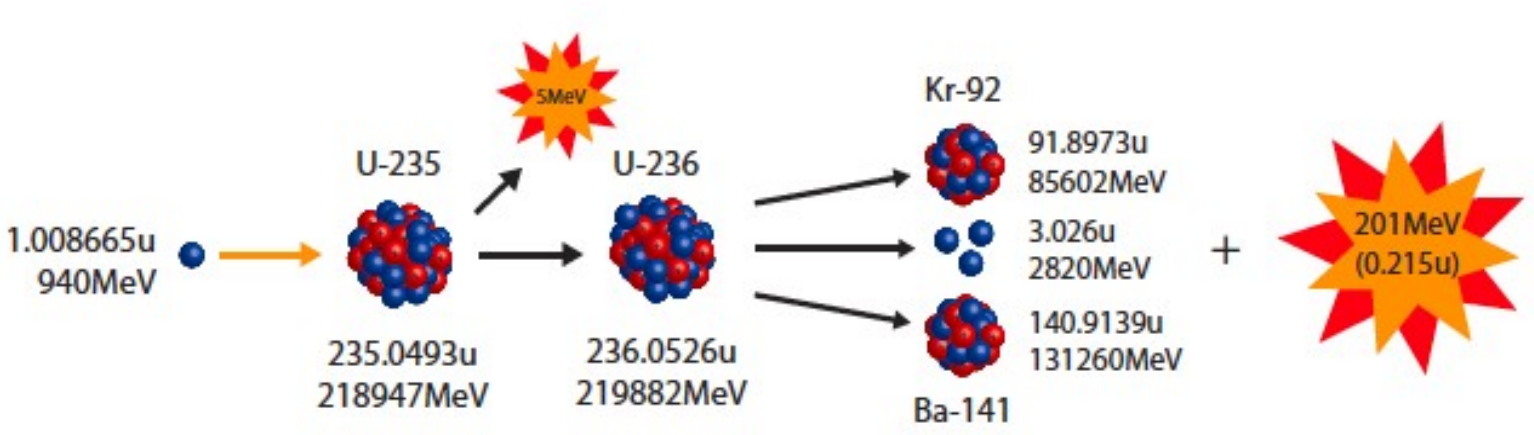
(Achieving $E = mc^2$)

Uranium Isotopes



U-235 is isotope that readily fissions upon capturing a neutron

$E = mc^2$ Illustrated



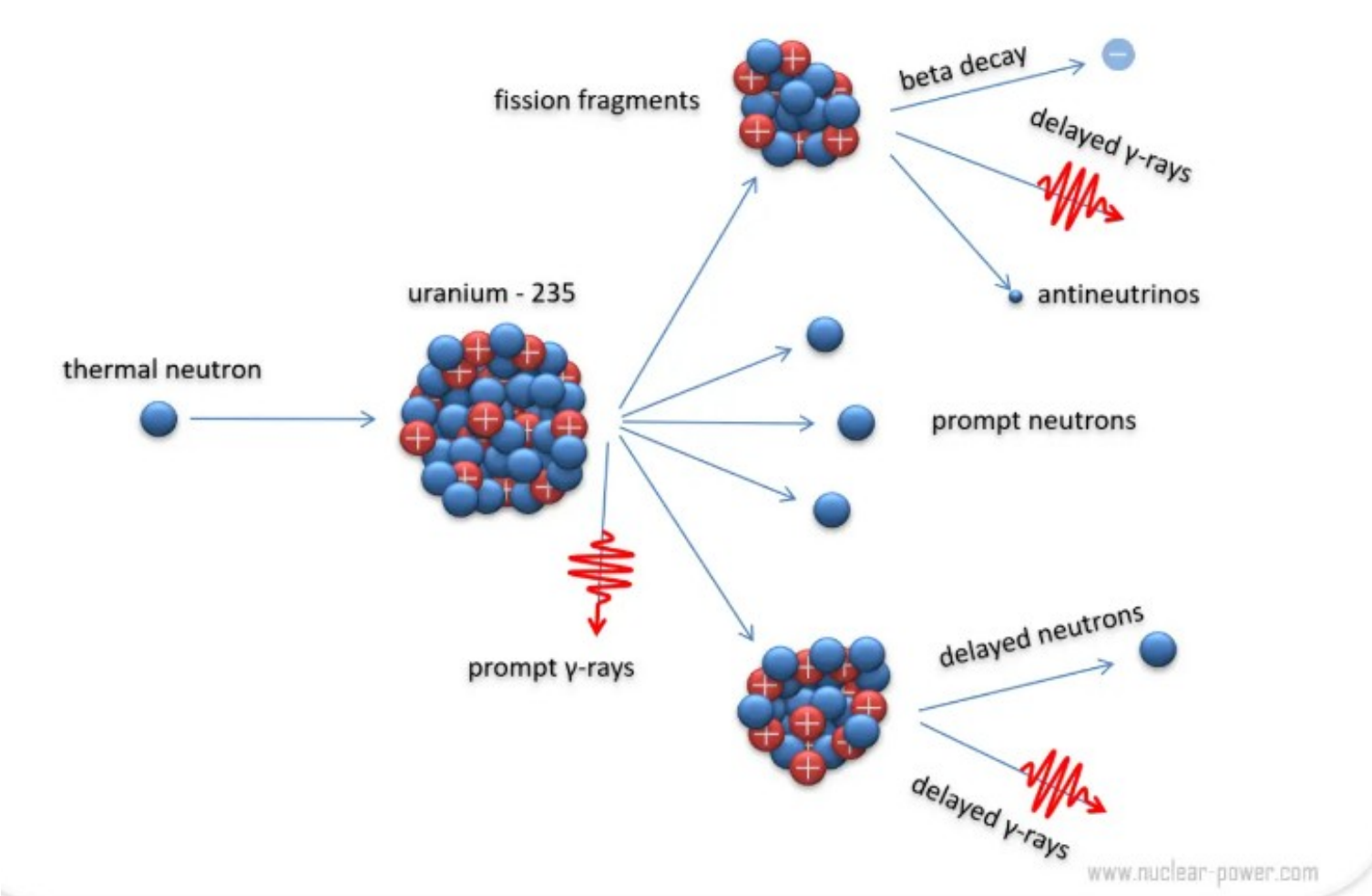
Mass defect (missing mass) = 0.215 atomic mass units (u), where $1u = 1.6606 \times 10^{-24}$ gram

$E = mc^2 \rightarrow (3.57 \times 10^{-28}\ kg)(3 \times 10^{8}\ m/s)^2 = 3.21 \times 10^{-11}\ Nm = 3.21 \times 10^{-11}\ J$

Since $1MeV = 1.602 \times 10^{-13}\ J$, $E \approx 200\ MeV$

Therefore, $1u \approx 930\ MeV$ (mass and energy equivalence)

Fission Energy Constituents



Nuclear Fission Energy Disposition

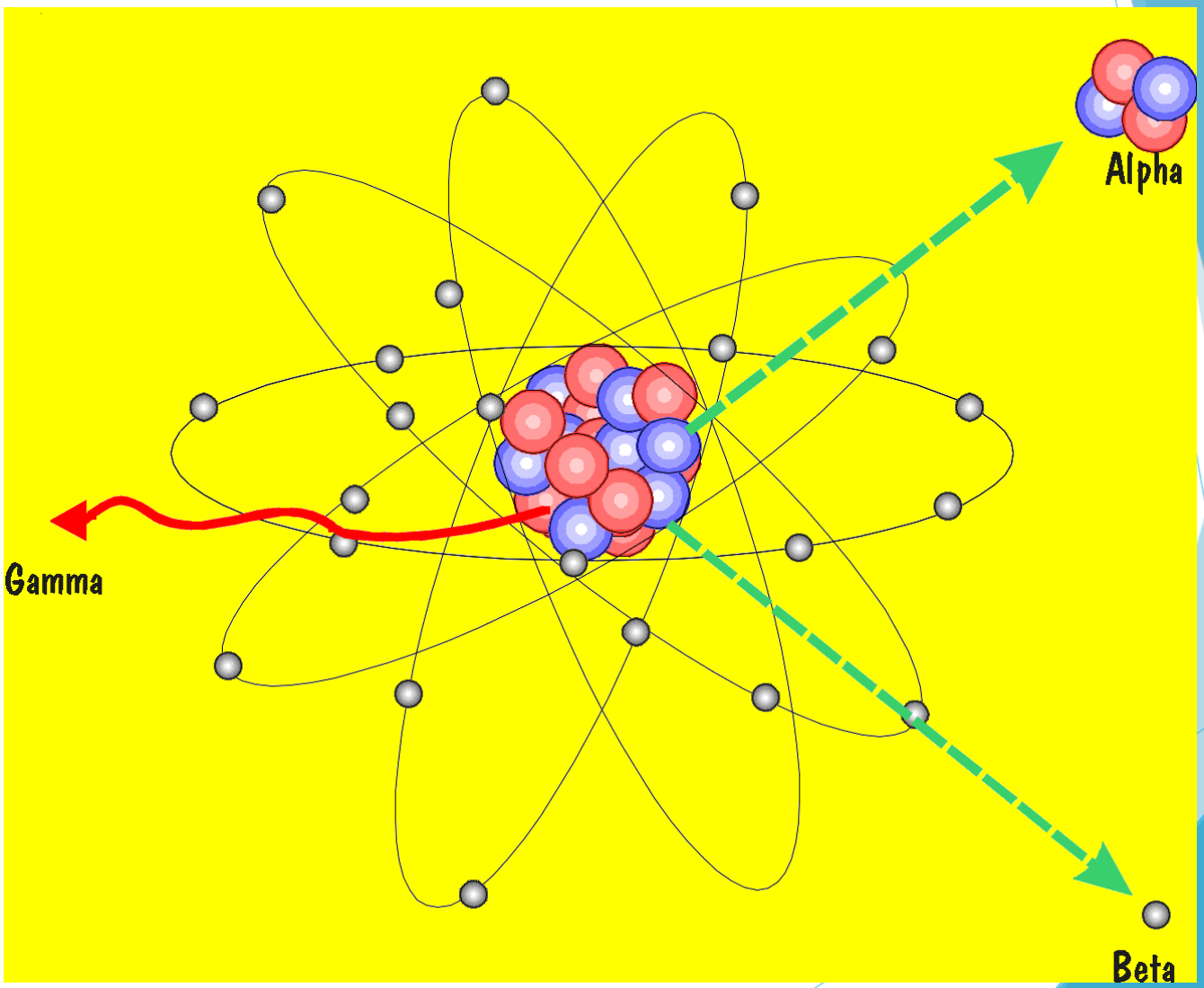
	Mev	%
Fission Fragment Kinetic Energy	168	84
Fission Neutron Kinetic Energy	5	2.5
Prompt Gamma Ray Energy	7	3.5
Fission Fragment Delayed Radiation		
Beta Particle Energy	8	4
Gamma-ray Energy	7	3.5
Radiative Capture Gamma-ray Energy*	5	2.5
Total	200	100

* Non-fission capture reactions contribute thermal energy to system

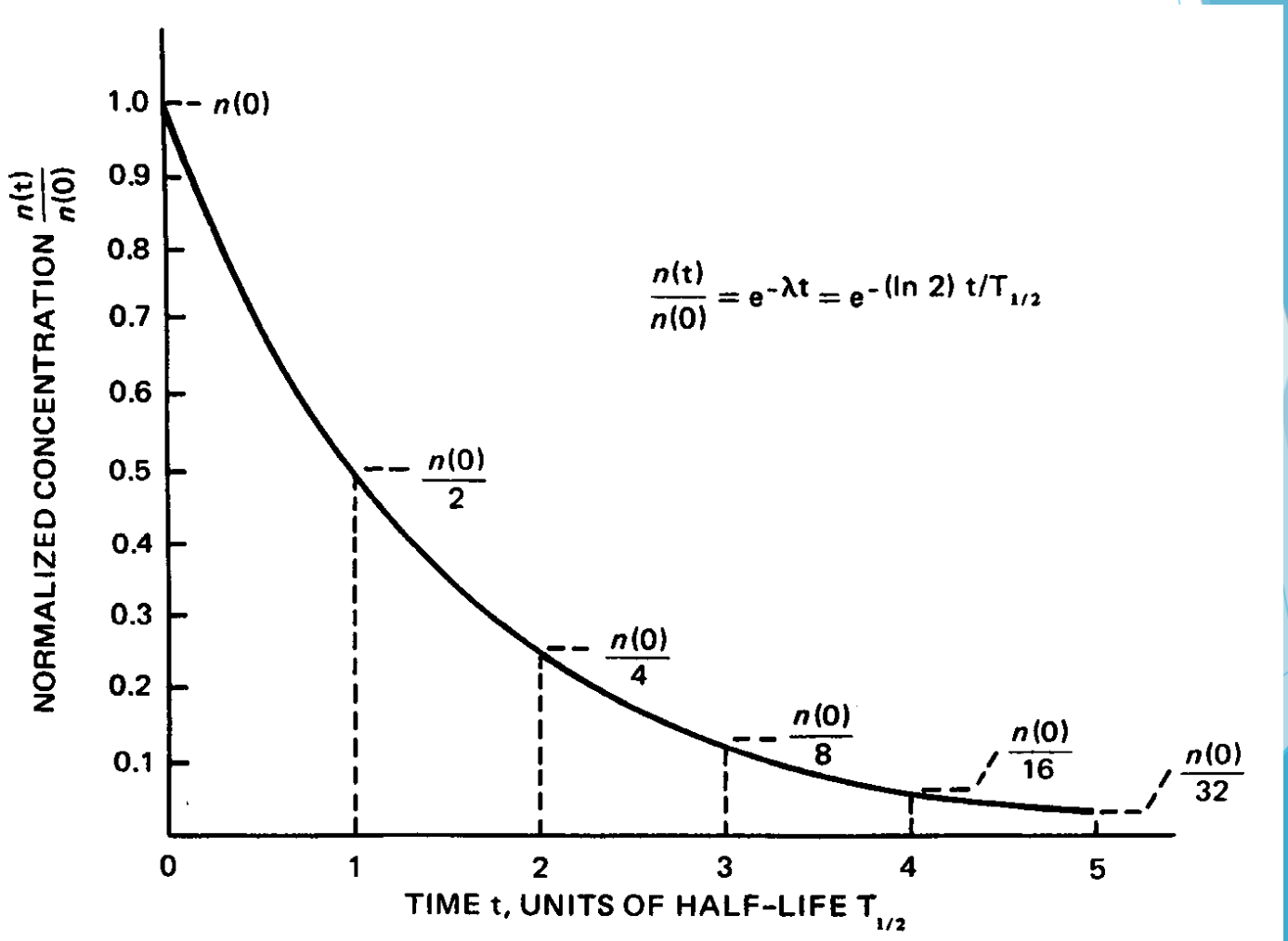
- Kinetic energy of fission fragments and delayed beta radiation energy deposited within the nuclear fuel material as thermal energy
- Most of fission neutron kinetic energy deposited within reactor cooling water (neutron moderator) as thermal energy
- Gamma-ray energy deposited in various reactor materials as thermal energy

U-235 Fission Fragment Distribution

Radioactivity



Radioactive Half-Life



Controlling the Chain Reaction

(Neutron Population Control)

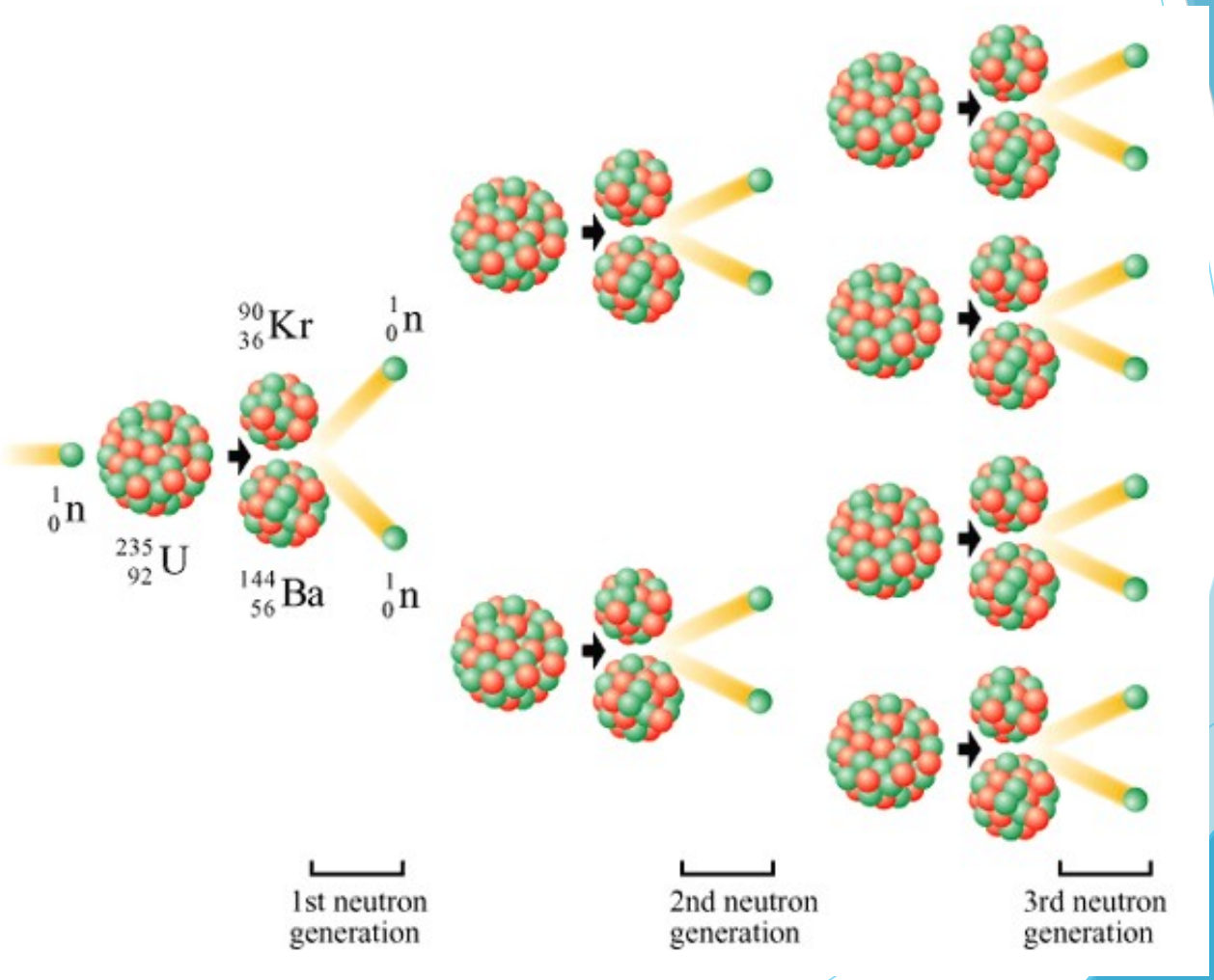
Nuclear Fission Chain Reaction

— ^{235}U

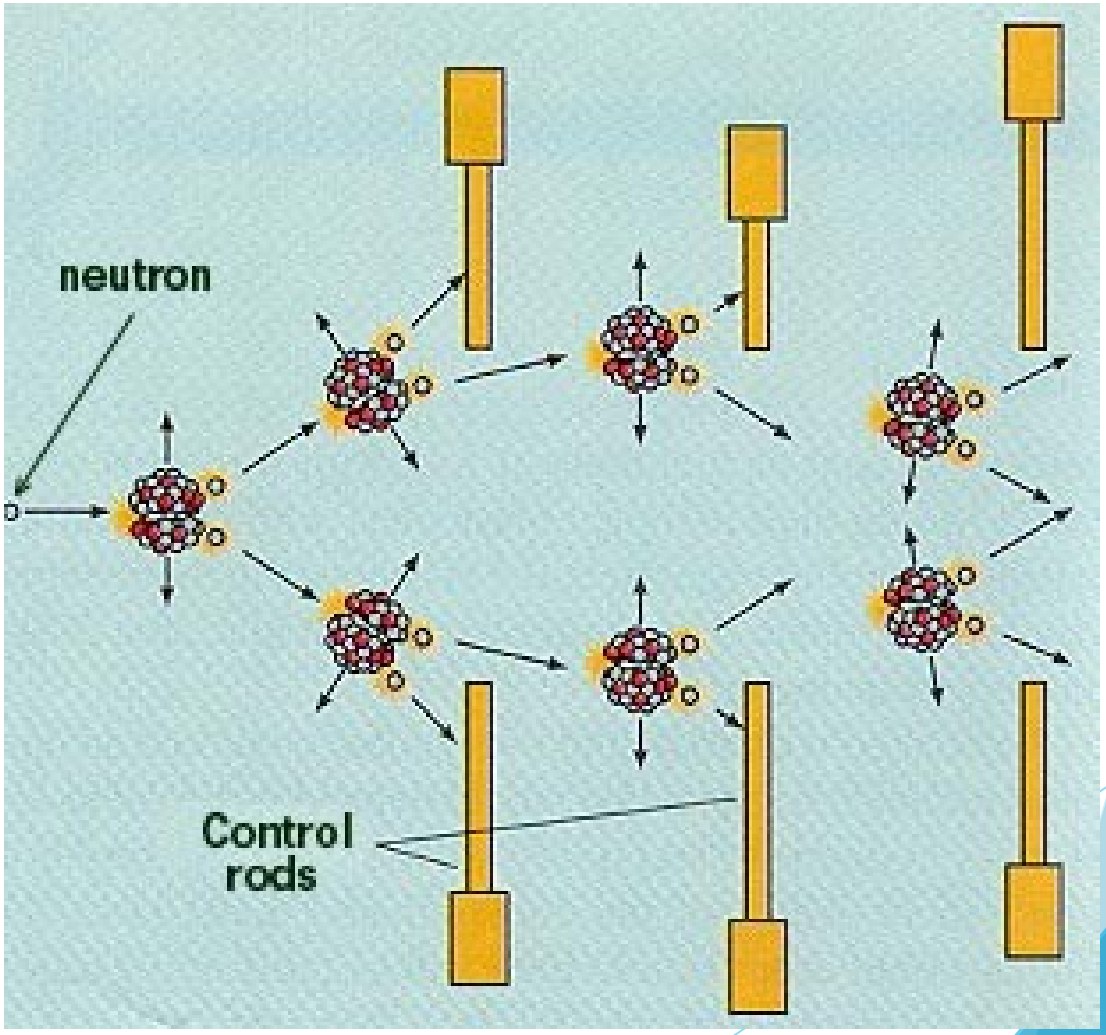
— Neutron

— Fission Product

Neutron Multiplication Produces a Chain Reaction

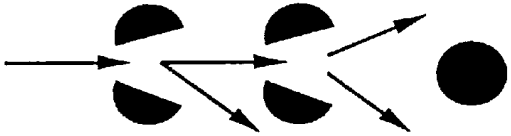


Chain Reaction Can Be Controlled With Neutron Absorbing Materials



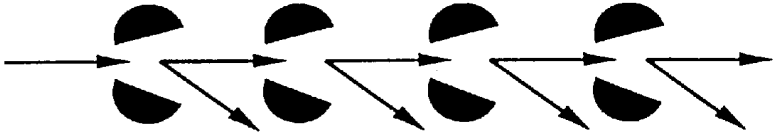
Three Possible Neutron Population Conditions

Subcritical



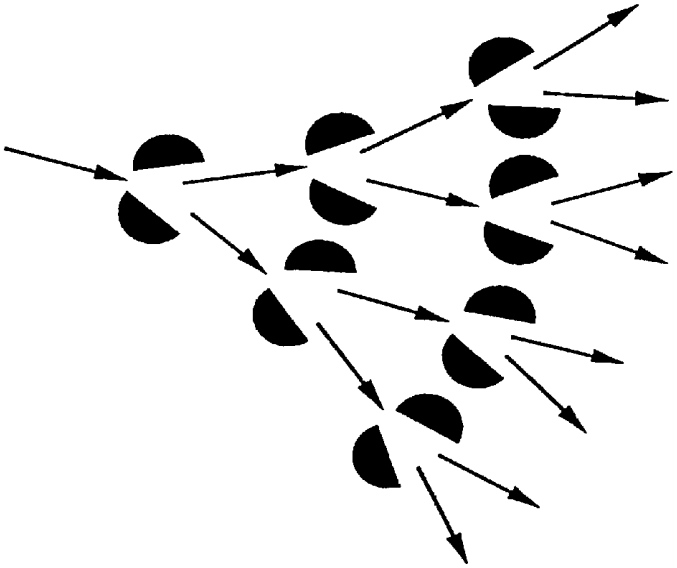
Too much neutron absorption; no sustained chain reaction

Critical



Constant neutron population

Super-critical



Too little neutron absorption; exponentially increasing neutron population

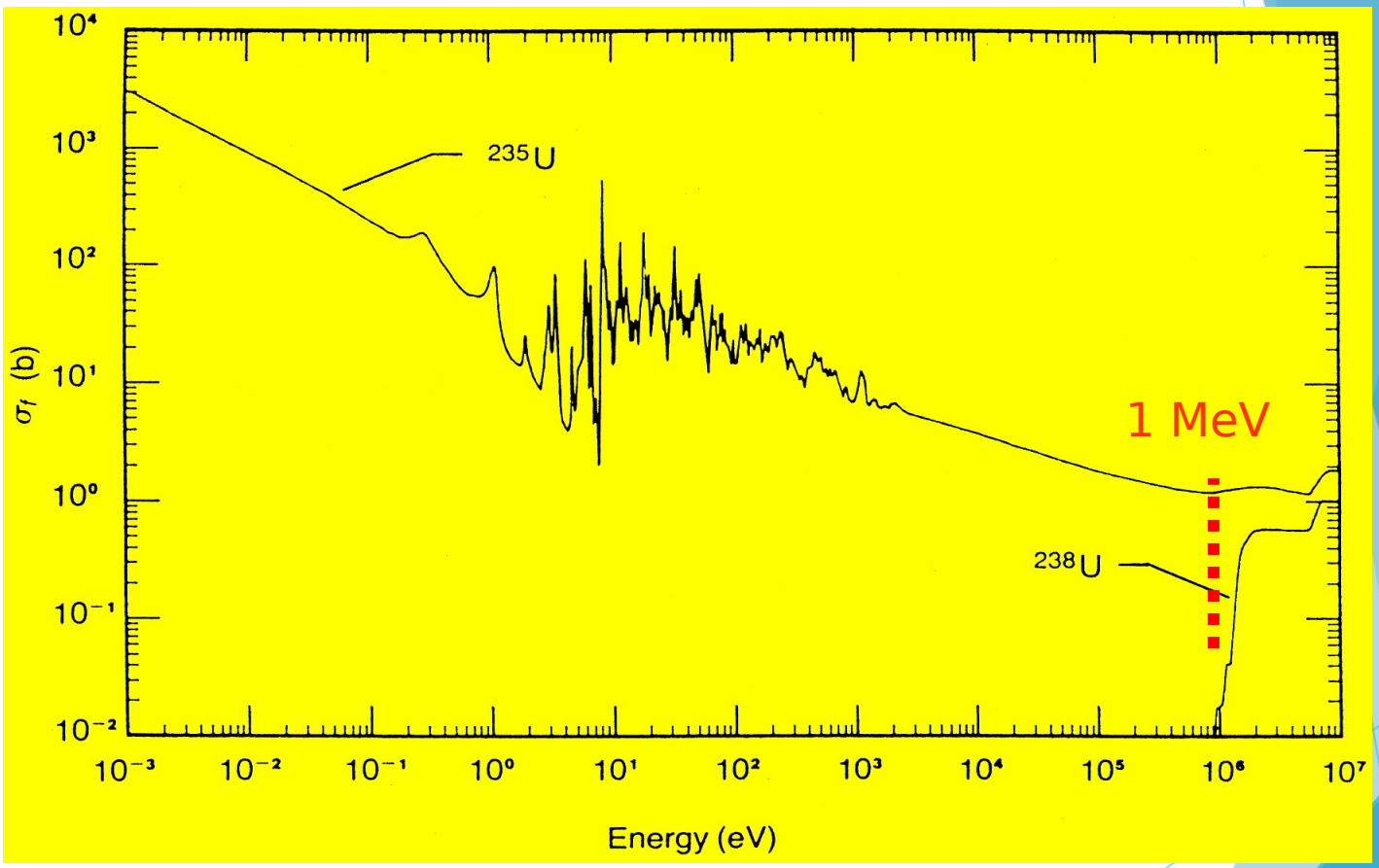
Slowing Down the Neutrons

(Increasing Neutron Fission Probability)

Neutron Moderation

- Fission (“fast”) neutrons have initial kinetic energy of ≈ 1 MeV (speed of approximately 14,000 km/s or 31.3 million miles per hour)
- Probability that U-235 atom can capture neutron at this energy (speed) to produce fission relatively low
- Need to consider how nuclear fission cross-section (propensity of an atom for neutron capture that will produce fission) varies with neutron energy
  - U-235 fission cross section increases with decreasing neutron energy

Uranium-235 Fission Cross-Section vs. Neutron Energy



Fission cross section (σ_f) is expressed in barns (b), where a
barn is 10^{-24} cm^2

Uranium-235 Fission Cross-Section vs. Neutron Energy

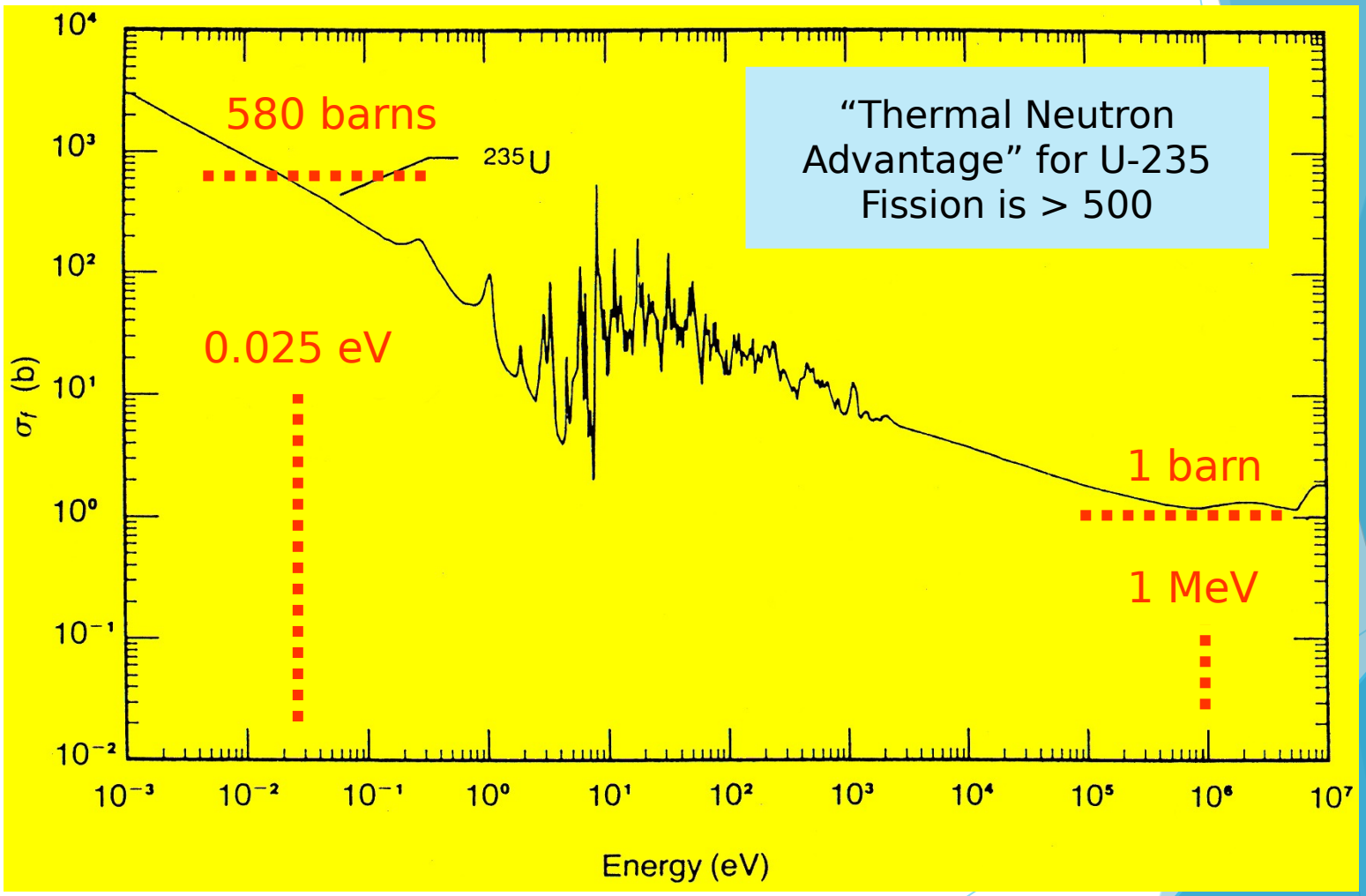
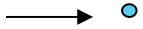
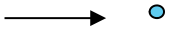


Illustration of Nucleus Cross-sectional Area vs. Incident Neutron Energy



High Energy Neutron

Relative Cross-sectional Area of Nucleus for Nuclide X



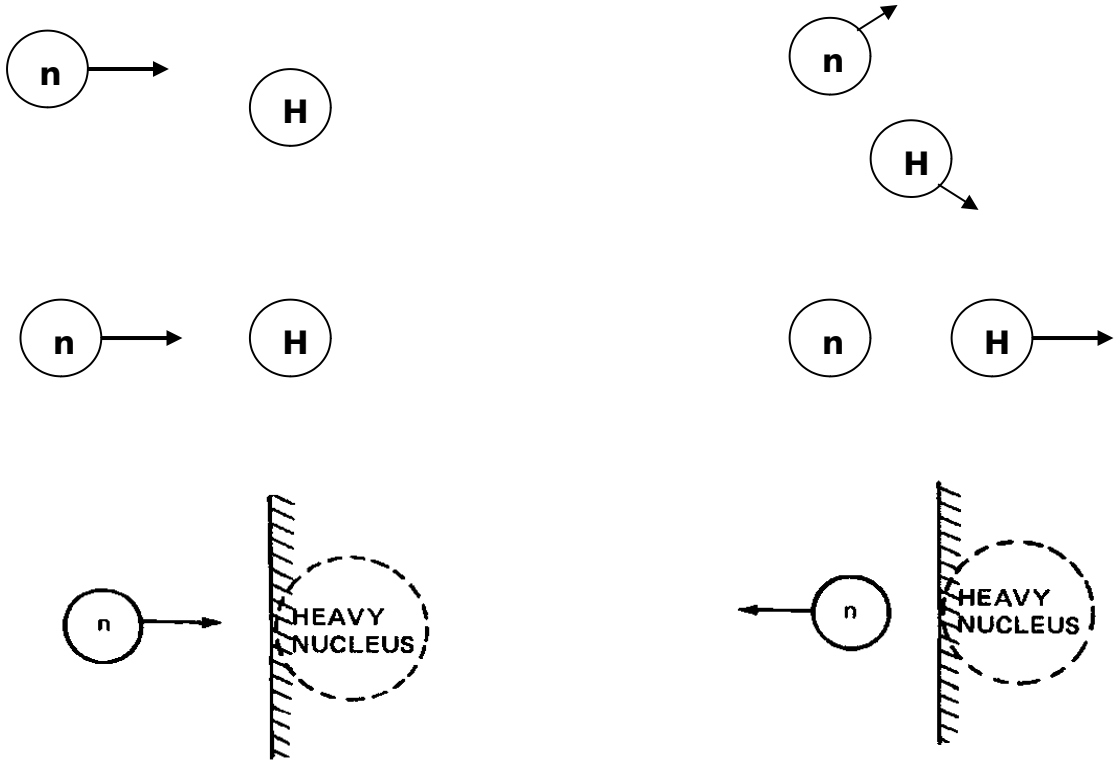
Low Energy Neutron

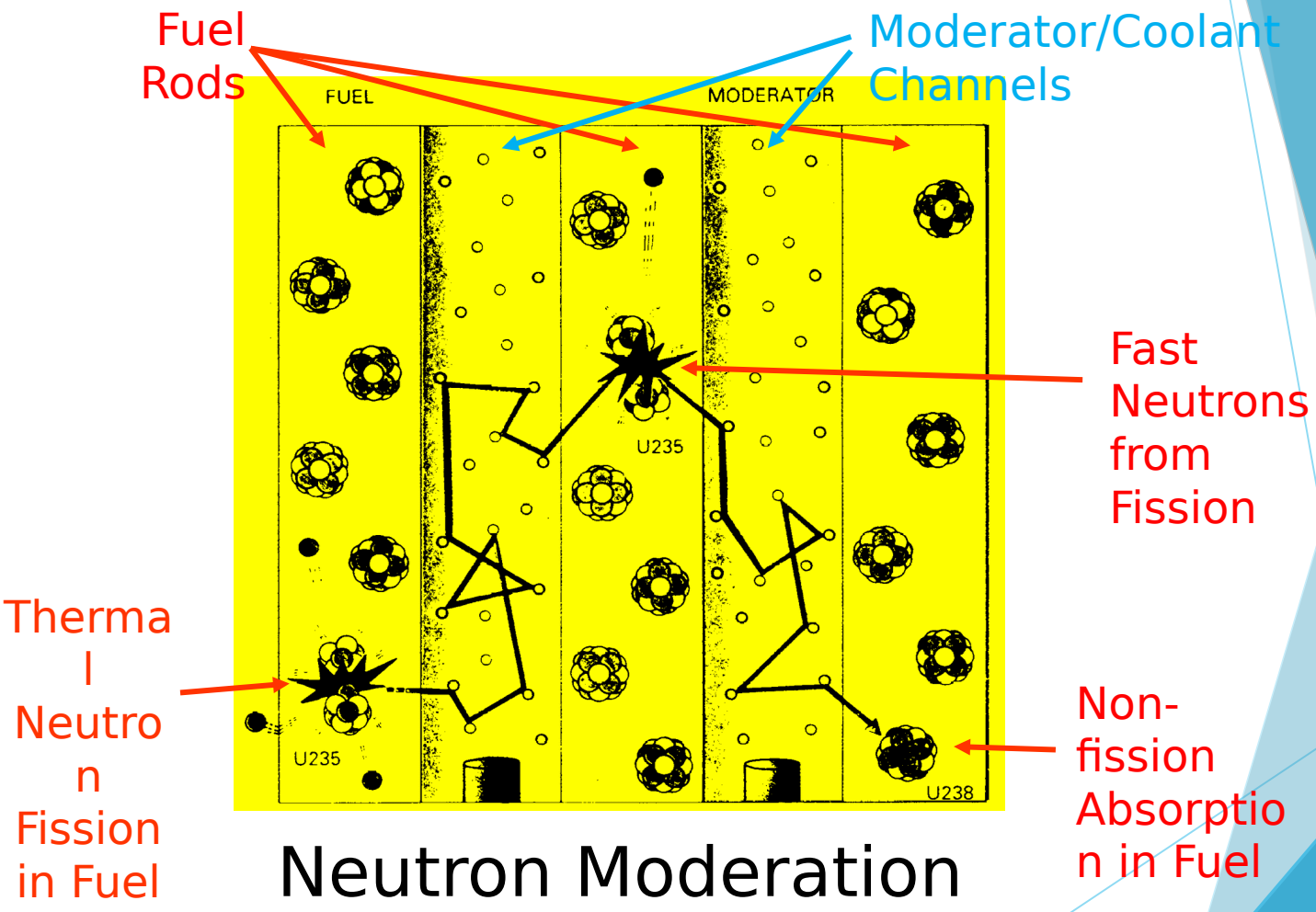
Probability of neutron interaction with a nucleus can be conceptualized as increasing cross-sectional area of target nucleus as neutron energy decreases

Water is a Neutron Moderator

- Necessary to moderate (slow down) fission neutrons to “thermal” kinetic energy of about 0.025 eV (speed of ≈ 2200 m/s or 4922 mph) to achieve maximum fission probability of U-235 atoms
- Water (H_2O) is effective neutron moderator because proton in hydrogen nucleus about same mass as neutron
- Elastic collisions between neutron and hydrogen nuclei cause neutron to lose energy with each collision

Neutron Scattering Events





Neutron Moderation

Moderator Effectiveness

Average number of elastic scattering collisions needed to slow down fast neutron with energy of 1 MeV to thermal energy of 0.025 eV :

Water (H_2O)	18 collisions
Heavy Water (D_2O)	24 collisions
Graphite (C)	111 collisions
Sodium (Na)	206 collisions
Uranium (U)	> 2000 collisions

Decay Heat

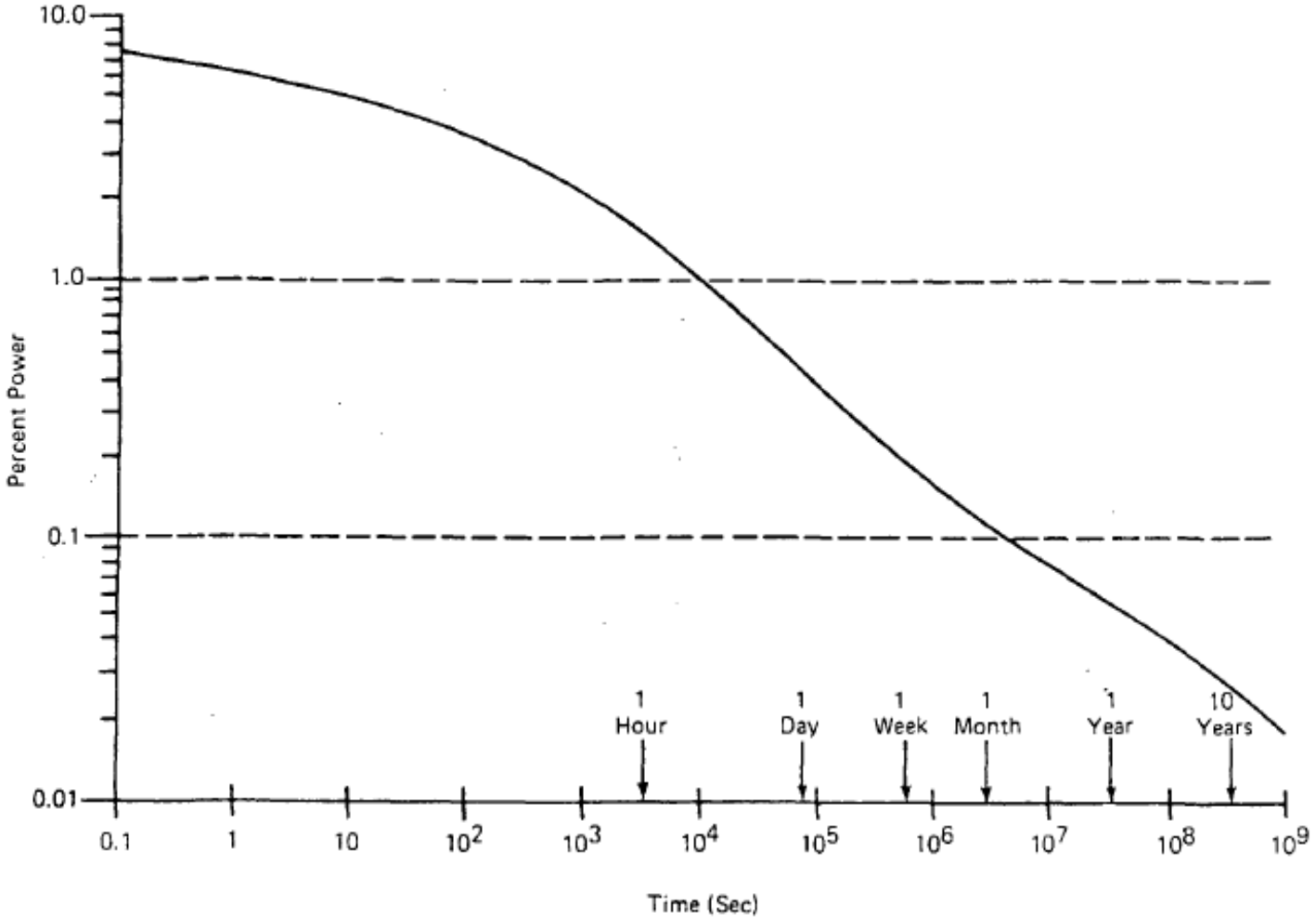
(Fission Product Radioactive Decay)

Nuclear Fission Energy Disposition

	Mev	%
Fission Fragment Kinetic Energy	168	84
Fission Neutron Kinetic Energy	5	2.5
Prompt Gamma Ray Energy	7	3.5
Fission Fragment Delayed Radiation		
Beta Particle Energy	8	4
Gamma-ray Energy	7	3.5
Radiative Capture Gamma-ray Energy	5	2.5
Total	200	100

Delayed radiation from fission product radioactive decay accounts for ≈7.5% of total fission energy and continues to generate heat in the fuel even after the fission process is terminated. This heat must be removed from the fuel to prevent overheating.

Decay Heat Production Following Reactor Shutdown



What About Nuclear Waste?

(Why We Should Reprocess Used Nuclear Fuel)

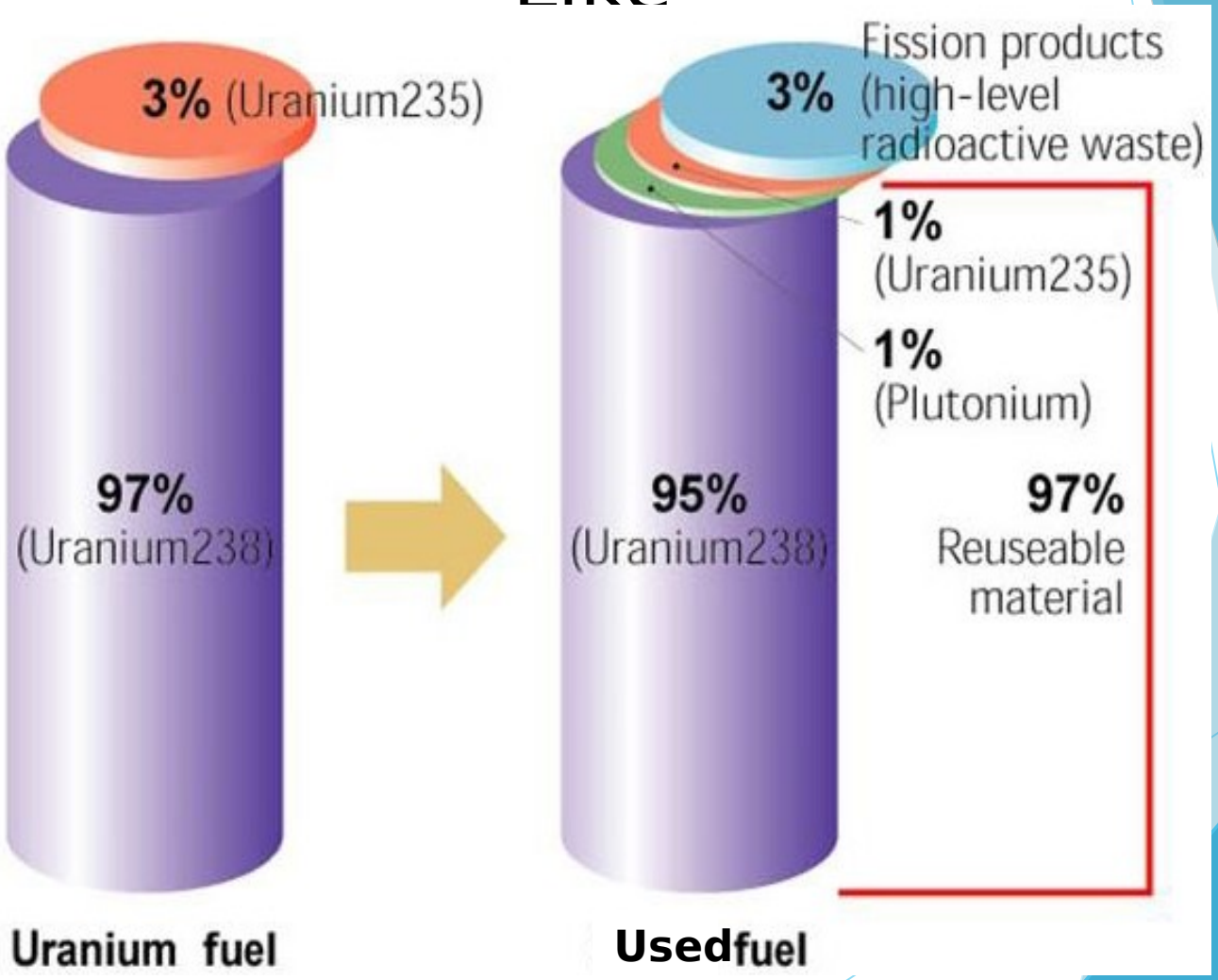
Connecticut Yankee Used Fuel

This is all the nuclear fuel used during the 30 years of reactor operation.

The waste volume could be reduced even more by reprocessing.

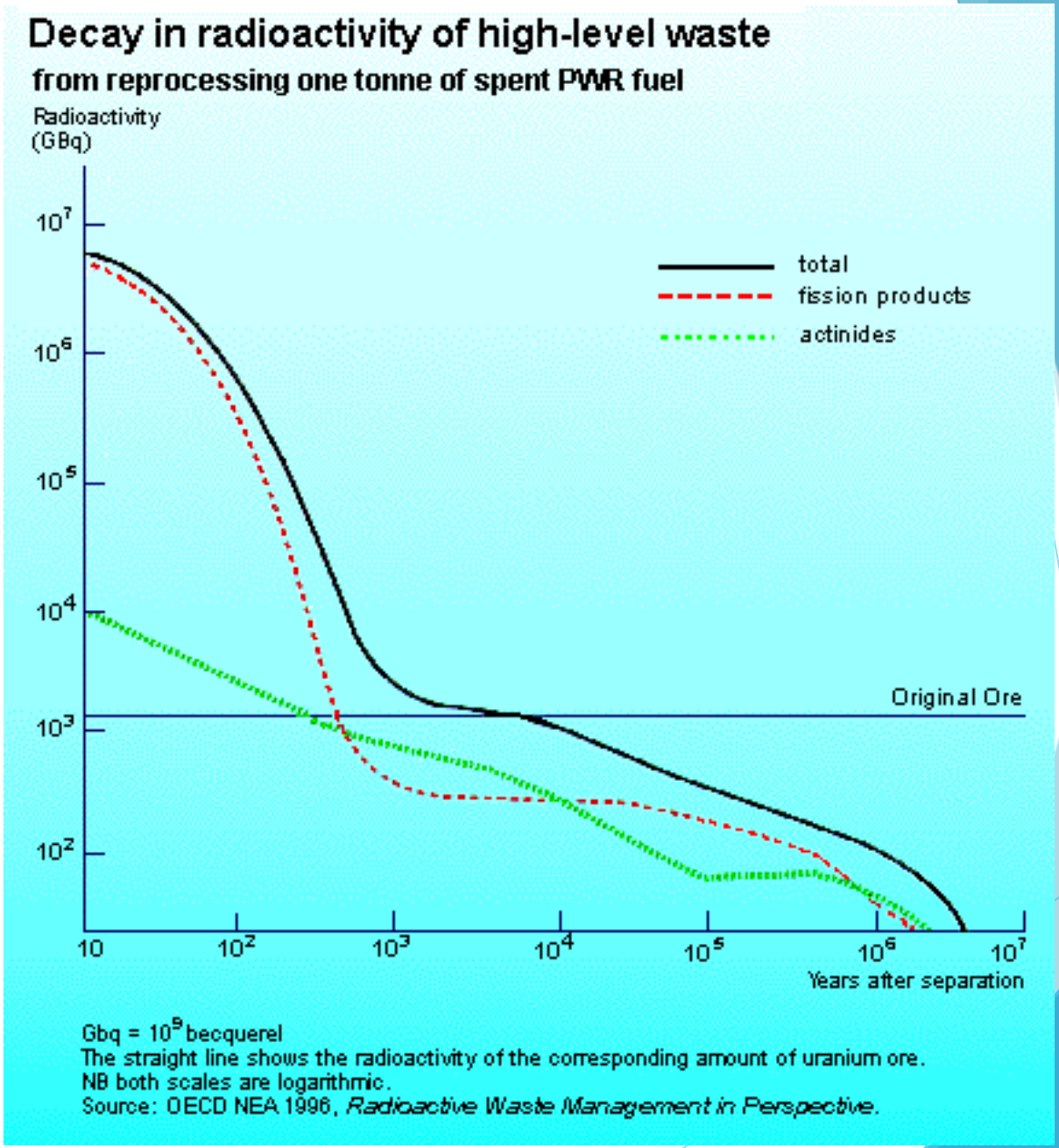
Used Nuclear Fuel Dry Storage Cask

What Used Reactor Fuel Really Looks Like

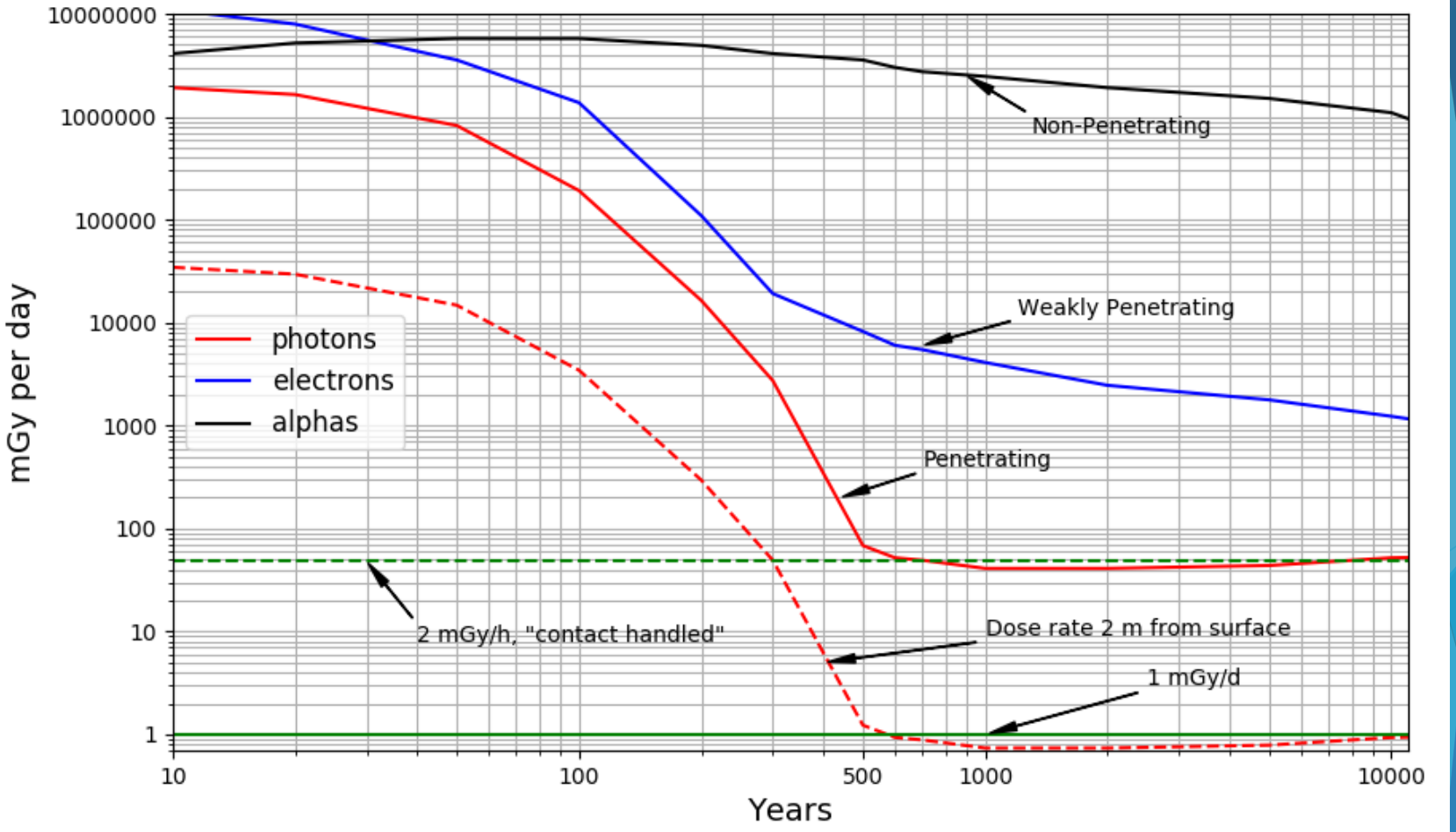


Used Nuclear Fuel is Not All Waste

Used Fuel Material	Material Disposition
Reprocessed plutonium and uranium	Fission in thermal, fast, or sub-critical reactors
Fuel cladding, filters	Less stringent storage as intermediate-level waste
Long-lived fission and activation products	Nuclear transmutation or geological repository
Medium-lived fission products Cs-137 and Sr-90	Medium-term storage as high-level waste
Useful radionuclides and noble metals	Industrial and medical uses


Decay in radioactivity of high-level waste
from reprocessing one tonne of spent PWR fuel
Radioactivity
(GBq)
10^7
10^6
10^5
10^4
10^3
10^2
total
fission products
actinides
Original Ore
10
10^2
10^3
10^4
10^5
10^6
10^7
Years after separation
Gbq = 10^9 becquerel
The straight line shows the radioactivity of the corresponding amount of uranium ore.
NB both scales are logarithmic.
Source: OECD NEA 1996, *Radioactive Waste Management in Perspective*.

Used Fuel Element Radiation Doses



Nuclear Waste Characterization

	By Volume	By Radioactive Content
High Level Waste	3%	95%
Intermediate Level Waste	7%	4%
Low Level Waste	90%	1%

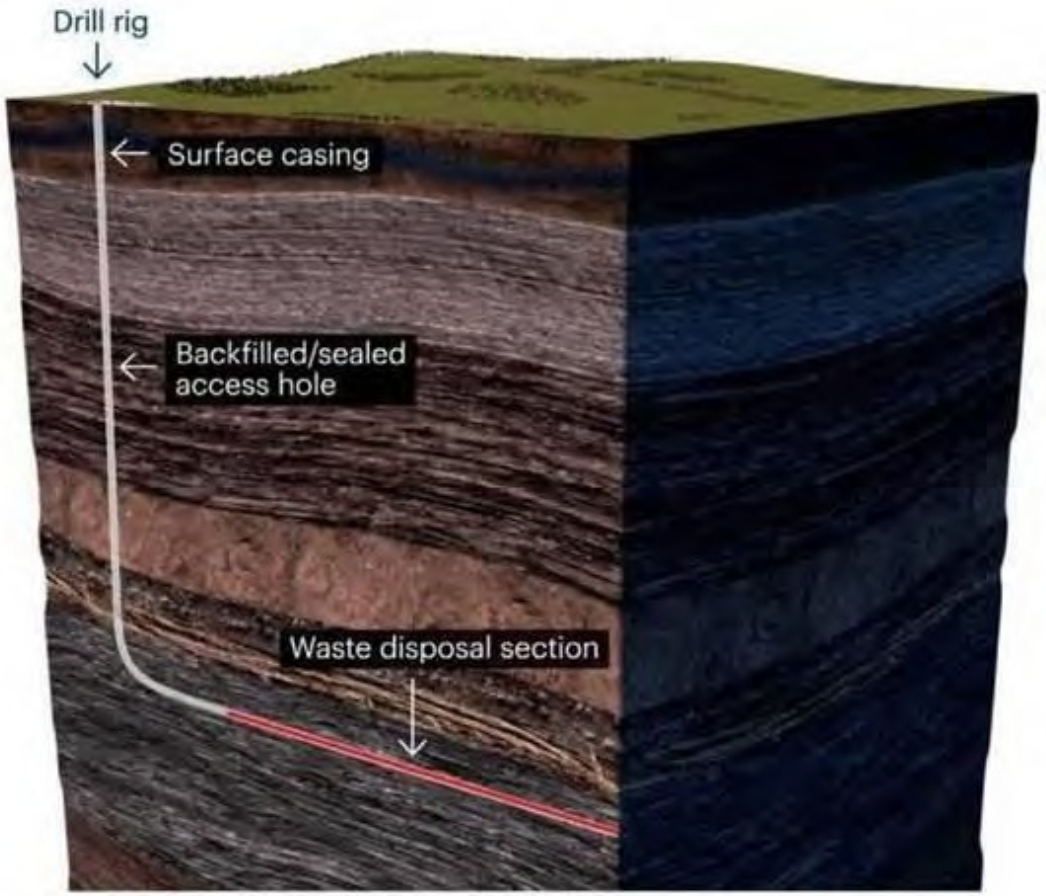
High level waste consists of long-lived and medium-lived fission products in nuclear fuel irradiated in reactor core for 3 to 4.5 years.

Intermediate level waste includes such things as used filters, steel components from within reactor, and some effluents from reactor coolant cleanup operations.

Low level waste consists of lightly-contaminated items like tools and work clothing from power
plant operations.

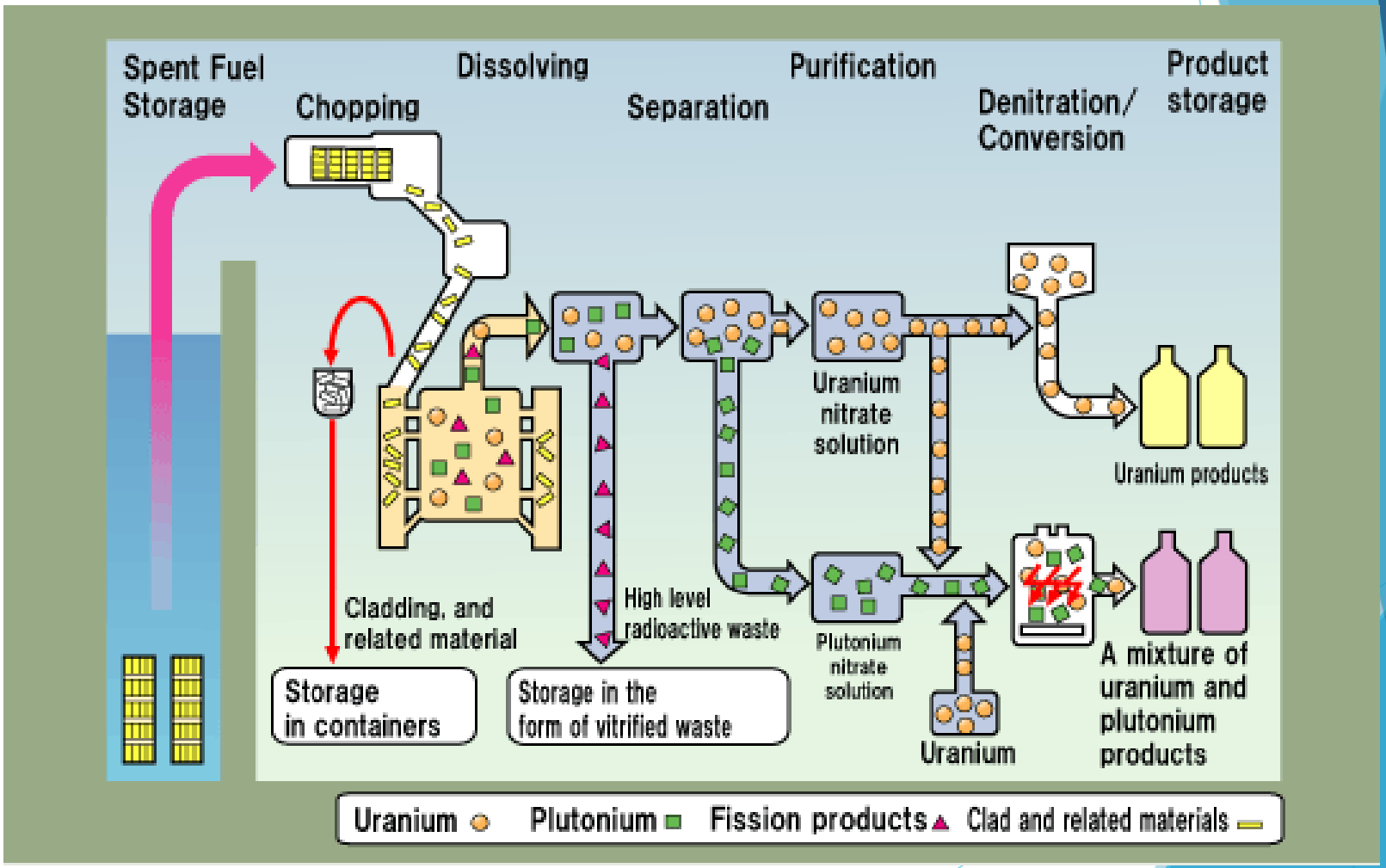
Nuclear fuel should be reprocessed to minimize amount of highly radioactive material that must be carefully managed.

Long-term Storage of Un-reprocessed Nuclear Fuel Using Fracking Technology



Source:
www.deepisolation.com

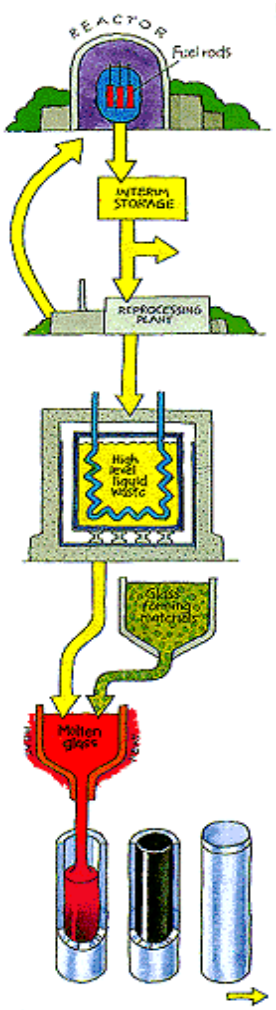
Nuclear Fuel Reprocessing



Used Nuclear Fuel Reprocessing

- Reprocessing removes certain fission products and shorter-lived actinide isotopes from used fuel so remaining used fuel can be manufactured into new fuel for advanced reactors
- Separated high-level waste from one year's operation of typical 1000 MWe nuclear reactor amounts to ≈ 700 kg
  - Liquid high-level wastes mixed with glass-forming materials and melted, then poured into robust stainless-steel canisters, which are then sealed by welding
  - Vitrified waste would fill about twelve canisters, each 1.3 m high, 0.4 m in diameter, and holding ≈ 400 kg of material

Nuclear Waste Solidification Process



- Glass forming material combined with liquid high-level waste to form borosilicate glass blocks that are placed inside stainless steel canisters for burial in high-level waste repository
- Borosilicate glass block shown below contains material that is chemically identical to high-level waste from nuclear fuel reprocessing
- Block this size would contain total high-level waste arising from nuclear electricity generation for one person throughout normal human lifetime

World Commercial Reprocessing Capacity

(tonnes U per year)

LWR Fuel	France, La Hague (1967)	1600
	UK, Sellafield (THORP - 1990)	1200
	Russia, Ozersk (Mayak - 1978)	400
	Japan (Rokkasho - 1977)	800
	Total LWR (approx)	4000
Other Nuclear Fuels	UK, Sellafield (Magnox - 1964)	1500
	India (PHWR, 4 plants - 1982)	300
	Total other (approx)	1800
	Total Commercial Capacity	5800

Dates are facility commissioning dates
Source: European Nuclear Society, July 29, 2008

Nuclear Resource and Reprocessed High Level Waste Comparison

Nuclear material required per person per lifetime:
1 golf ball

Volume of waste per person generated for their lifetime. These fission products remain radioactive for only 300 years.

Wasteful Status Quo – Economically and Environmentally

- American taxpayers shelling out billions of dollars annually to manage and store used nuclear fuel
- Tens of billions of dollars in Nuclear Waste Fund collected from utility ratepayers, but trapped by congressional gridlock
- Not reprocessing perpetuates cycle of mining more uranium that scars landscapes, encroaches on aquifers, and consumes significant amounts of energy
- Reprocessing saves money, secures energy, and shrinks waste

“Waste” Considerations for Electricity-Generating Systems

Annual Waste Produced by Operation of 1000 MWe Power Plant

Plant Type	Amt of Electricity Produced (MWh)	Spent Nuclear Fuel (tons)	Coal Ash (tons)*	Sulfur Dioxide (tons)	Nitrogen Oxide (tons)	Carbon Dioxide (tons)	Small Particu-lates (tons)	Carbon Mon-oxide (tons)	Total Annual Waste (tons)	Waste per kWh (lbs)
Nuclear	7,971,600	27**	0	0	0	0	0	0	27	0.007
Coal	6,683,880	0	400,000	20,000	20,400	7,400,000	100	1,440	7,841,940	2,347
Natural Gas	998,640	0	0	2	157	199,472	12	68	199,711	400
Petroleum (Oil)	1,173,840	0	0	2248	898	328,655	168	66	332,036	566

* Some radioactive content

** Non-reprocessed used fuel

Life-Cycle "Waste" Comparisons

- Only considering annual waste production from electrical-generating system operation results in incorrect understanding of "waste" generation
- True picture of "waste" generation must be based on system life-cycle comparisons
- Renewable energy systems not as "benign" as some claim
  - Millions of pounds of polluted sludge and contaminated water are annual byproducts of solar panel manufacturing
  - Wind turbine generators manufactured with rare-earth metals, mining and processing of which creates millions of tons of toxic waste
  - Roads and pads developed for ultimate placement of wind turbines affects environment

Emissions Produced by 1 Kilowatt-hour of Electricity Based on Life-Cycle Analysis

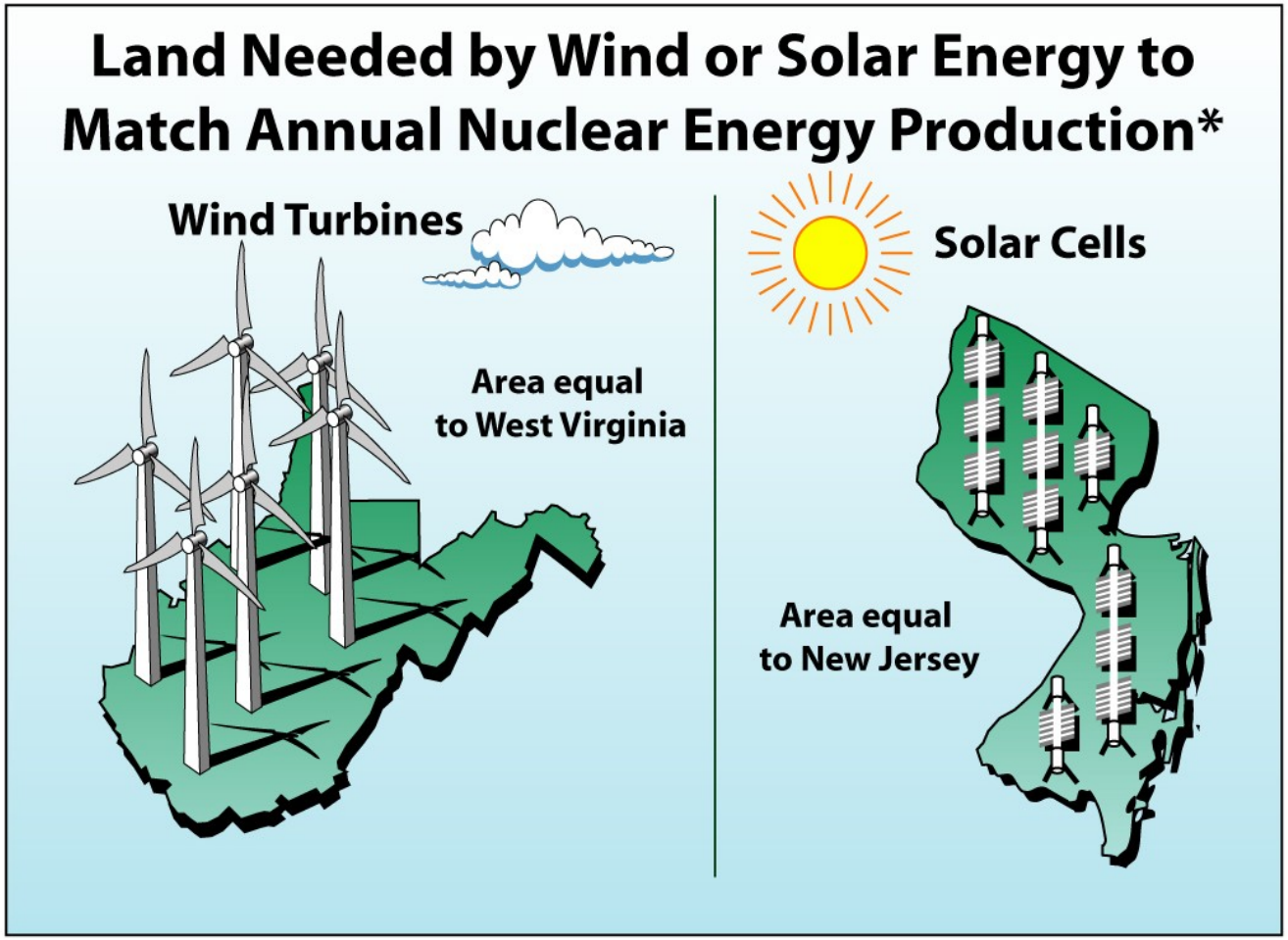
Generation Option	Greenhouse gas emissions (in gram equiv. CO_2/kWh)	Sulfur dioxide emissions (in milligrams/kWh)	Nitrogen oxide emissions (in milligrams/kWh)	Particulate matter (in milligrams /kWh)
Hydropower	2 – 48	5 – 60	3 – 42	5
Nuclear	2 – 59	3 – 50	2 – 100	2
Wind	7 – 124	21 – 87	14 – 50	5 – 35
Solar photovoltaic	13 – 731	24 – 490	16 – 340	12 – 190
Biomass forestry waste combustion	15 – 101	12 – 140	701 – 1,950	217 – 320
Natural gas (combined cycle)	389 – 511	4 – 15,000[*]	13 – 1,500	1 – 10
Coal – modern plant	790 – 1,182	700 – 32,321	700 – 5,273	30 – 663

[*] The sulfur content of natural gas when it comes out of the ground can have a wide range of values. When the hydrogen sulfide content is more that 1 percent, the gas is usually known as “sour gas.” Normally, almost all of the sulfur is removed from the gas and sequestered as solid sulfur before the gas is used to generate electricity. Only in the exceptional case when the hydrogen sulfide is burned would the high values of sulfur dioxide emissions occur.

Land Use Considerations for Nuclear vs. Renewable Electricity-Generating Systems

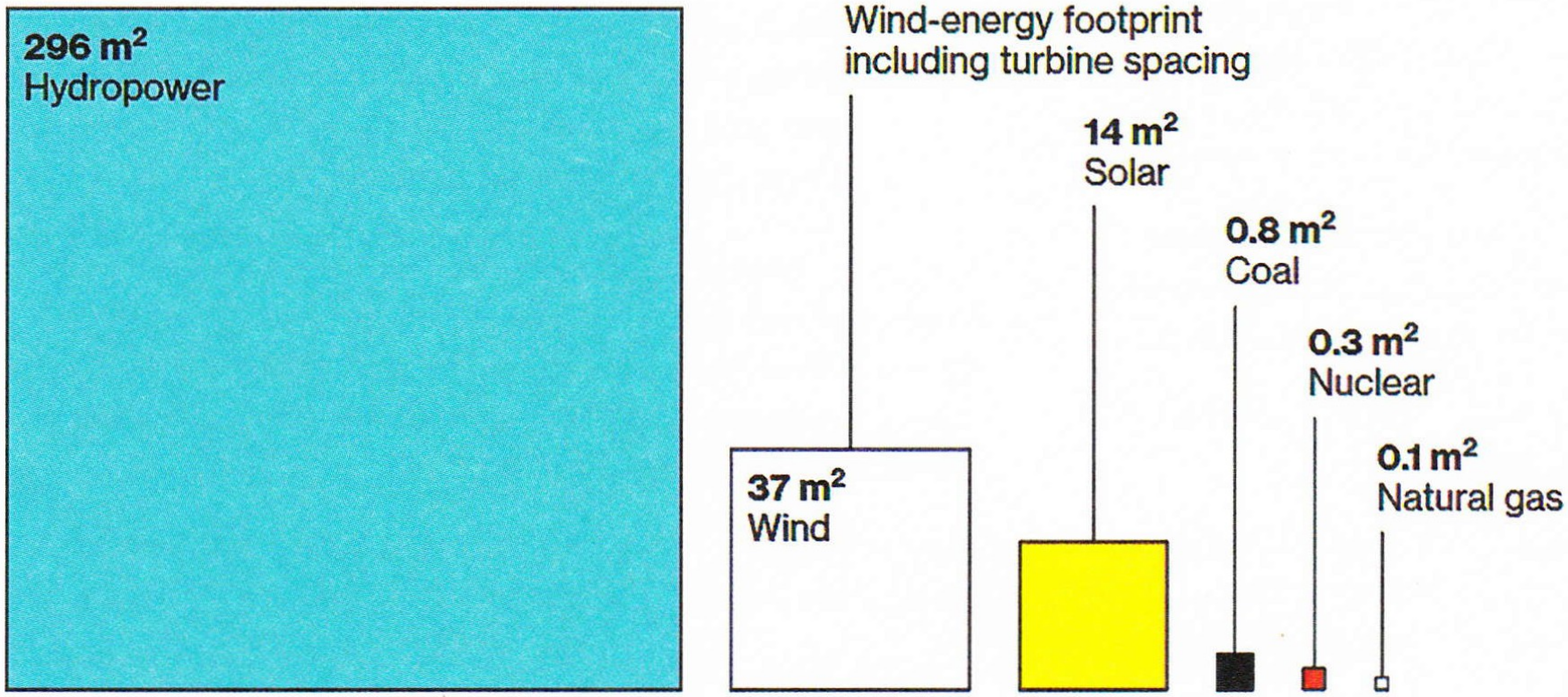
Land Requirements for Generating 1000 MW of Electricity

Method for Generating Electricity	Land Area (sq. miles)
Photovoltaic*	**100[a]**
Wind**	**550[a]**
Hydroelectric	**1500[b]**
Biomass	**2600[c]**
Nuclear	**1.5**



Note: The 93 nuclear power plants currently operating in the U.S. require approximately 140 square miles of land, somewhat more than twice the land area of the District of Columbia.

Land area needed to power a flat-screen TV, by energy source



Note: Assumes 100-watt television operating year-round

Source: van Zalk, John, Behrens, Paul, 2018, The Spatial Extent of Renewable and Non-Renewable Power Generation

Advantages of Nuclear Power

- Provides base load electricity (24 hours a day, 365 days a year)
- Expandable to meet need
- No emissions during operation
- Low land use
- Does not deplete useful resources
  - No other commercial use for uranium
- Sufficient fuel is available
  - Once-through fuel cycle – hundreds of years
  - Recycle and breeder reactors - thousands of years

Supplemental Slides

Medium Half-Life Fission Products

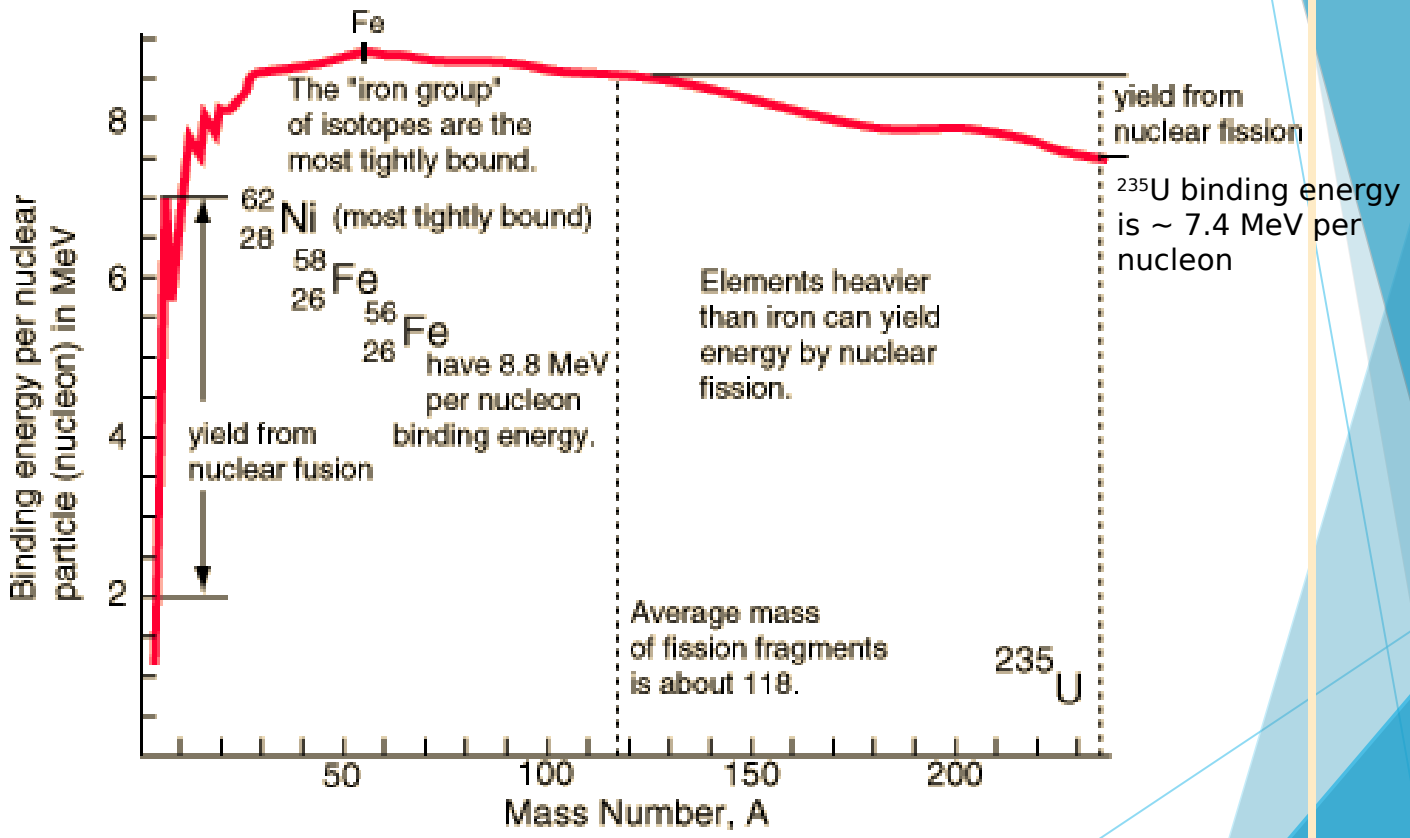
Fission Product	Half Life (years)	Decay Energy MeV	Decay Mode
^{155}Eu	4.76	0.252	β,γ
^{85}Kr	10.76	0.687	β,γ
^{113m}Cd	14.1	0.316	β
^{90}Sr	28.9	2.826	β
^{137}Cs	30.23	1.176	β,γ
^{121m}Sn	43.9	0.390	β,γ
^{151}Sm	90	0.077	β

Illustration of β,γ Radioactive Decay

Long Half-Life Fission Products

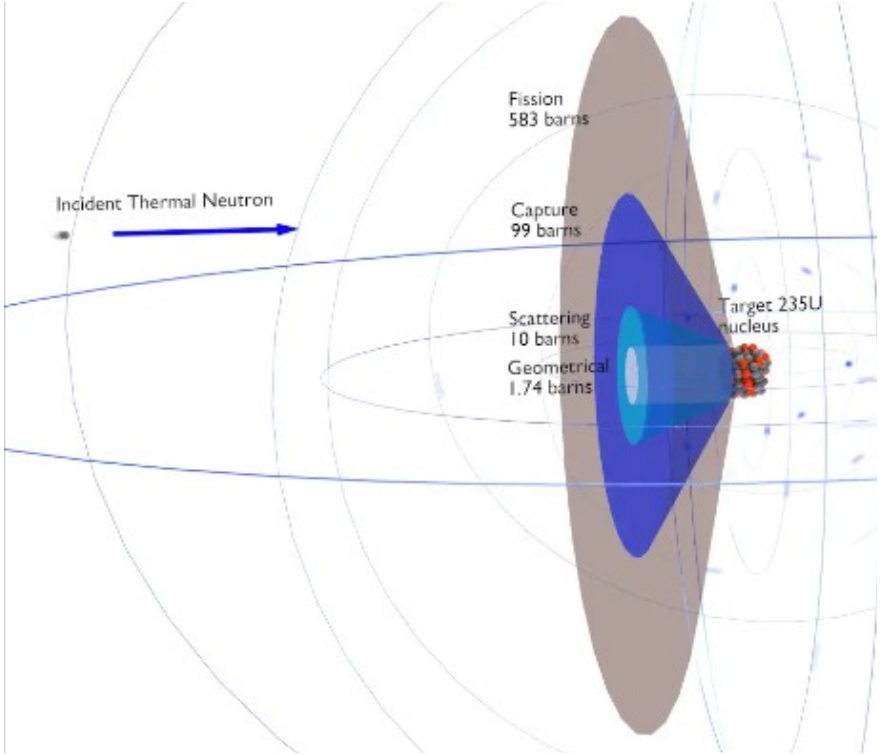
Fission Product	Half Life (years)	Decay Energy MeV	Decay Mode
^{99}Tc	211,000	0.294	β
^{126}Sn	230,000	4.050	β,γ
^{79}Se	327,000	0.151	β
^{93}Zr	1,530,000	0.091	β,γ
^{135}Cs	2,300,000	0.269	β
^{107}Pd	6,500,000	0.033	β
^{129}I	15,700,000	0.194	β,γ

Binding Energy per Nucleon

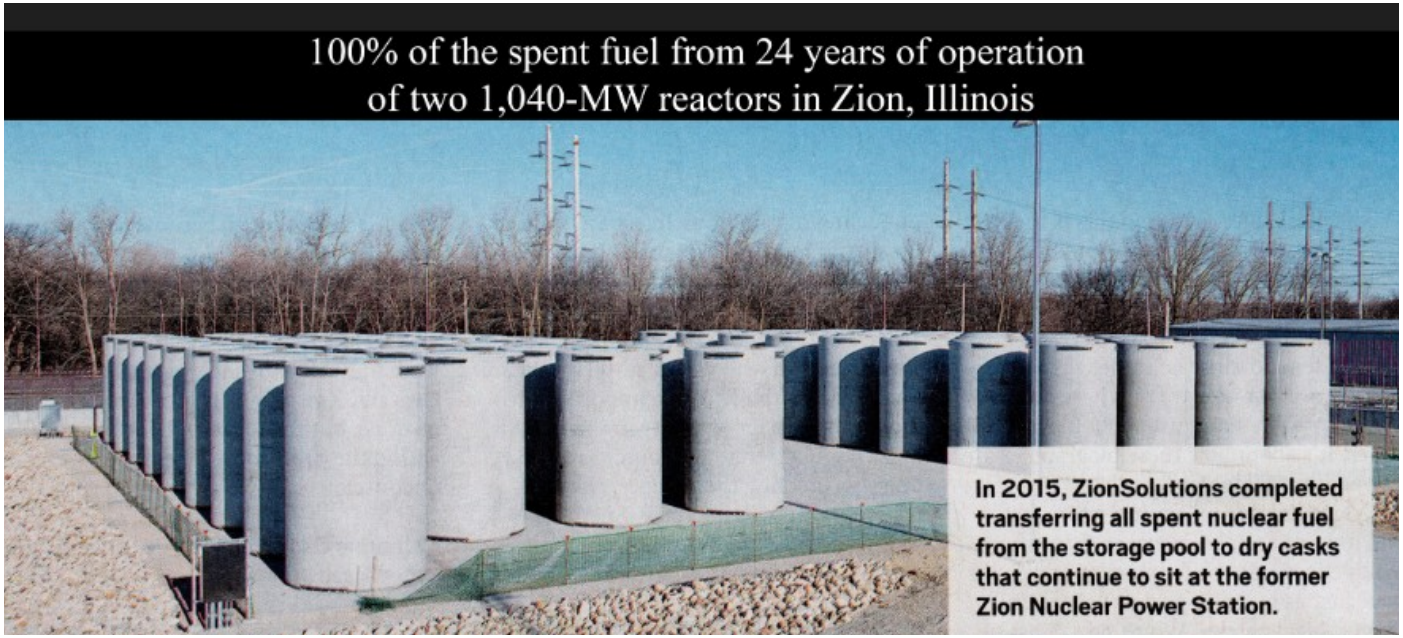


^{235}U binding energy is ~ 7.4 MeV per nucleon

Illustration of U-235 Cross Sections for Neutron Interactions



Zion NPP Used Fuel



Concrete slab is much smaller than a neighborhood Wal-Mart

Nuclear Fuel Reprocessing